In the News

New NASA Administrator (replacing Sean O'Keefe):

Mike Griffin

No robotic servicing mission for Hubble

Normal Galaxies

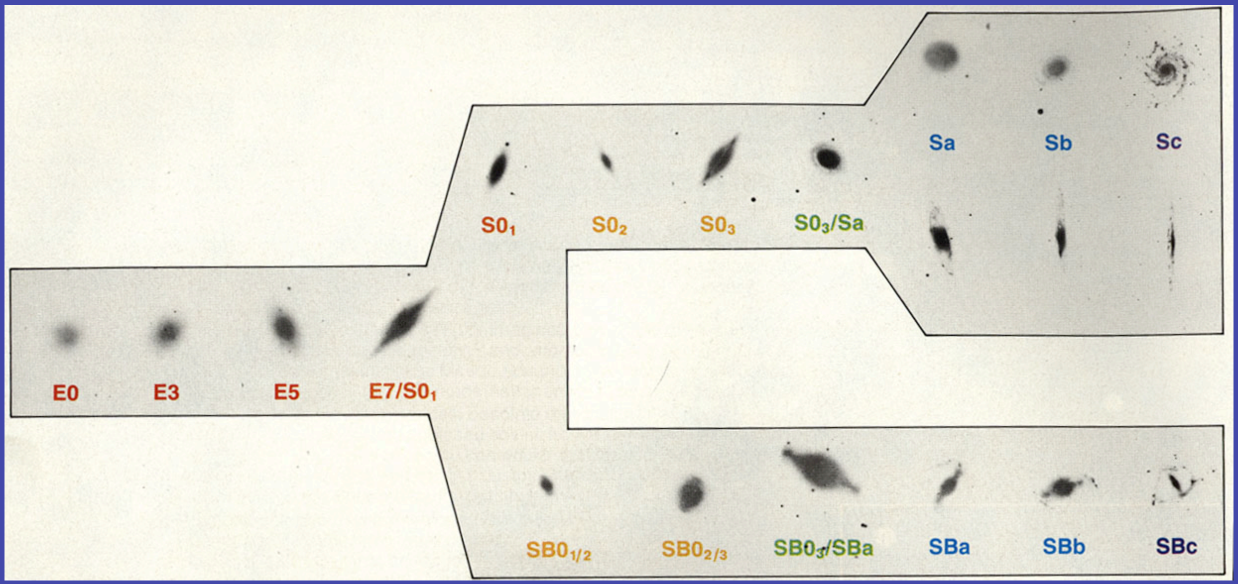
- A galaxy is a gravitationally bound aggregate of dark matter. Minor constituents of galaxies include gas, dust, stars

- Most (all?) contain supermassive black holes ($M>10^6 M_\odot$)

- Normal galaxies are those in which the supermassive black hole is not accreting rapidly

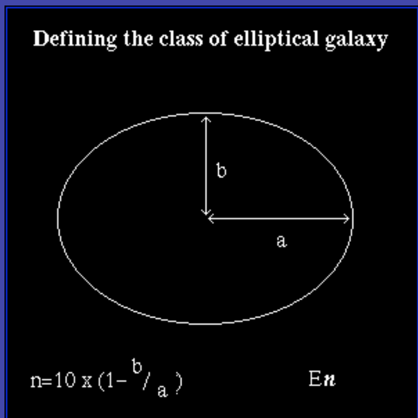
The Tuning-Fork Diagram

Galaxies come in certain morphologies: Elliptical, Spiral and Irregular.
Edwin Hubble arranged these morphologies in the shape of a tuning fork, suggesting an evolutionary sequence



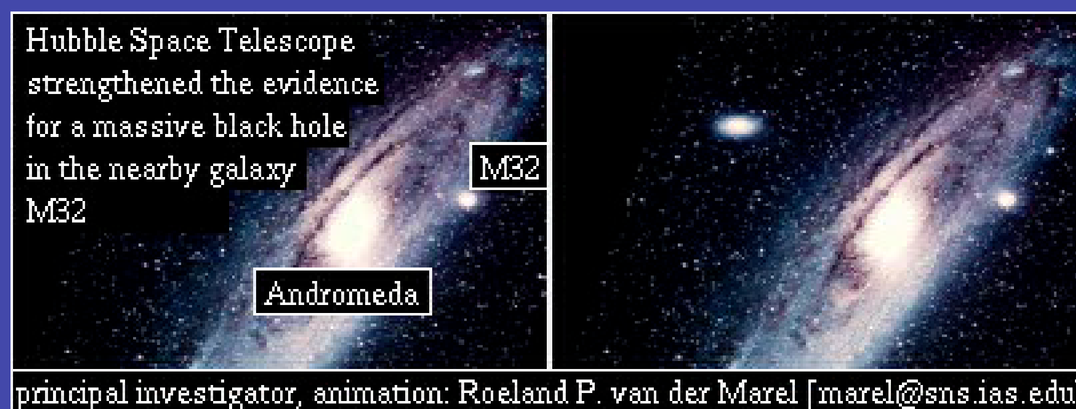
http://www.star.le.ac.uk/edu/galaxies/index.html

Ellipticals



- Fairly featureless
- range in shape from round (E0) to nearly flat(E7)
- Contain mostly old, red stars
- wide range in masses: 10^5 to 10^{13} $M_\odot$
- Diameters 1-100 kpc
- Formed earlier than spirals?
- Some have gas and dust, some activity

M87 (E1)



Irregular Galaxies

Most numerous type of galaxy (aside from dwarf ellipticals)

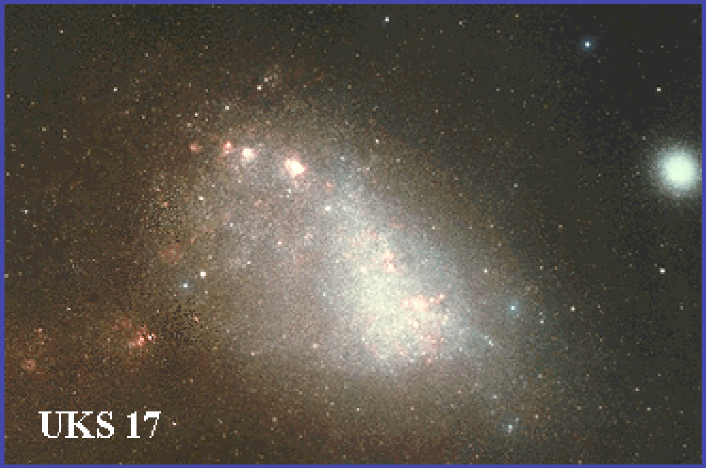
no morphology or ordered angular momentum

lots of gas and dust

Star formation

nearest examples: Large Magellanic Cloud, Small Magellanic Cloud - satellites of Milky Way

LMC: 50 pc

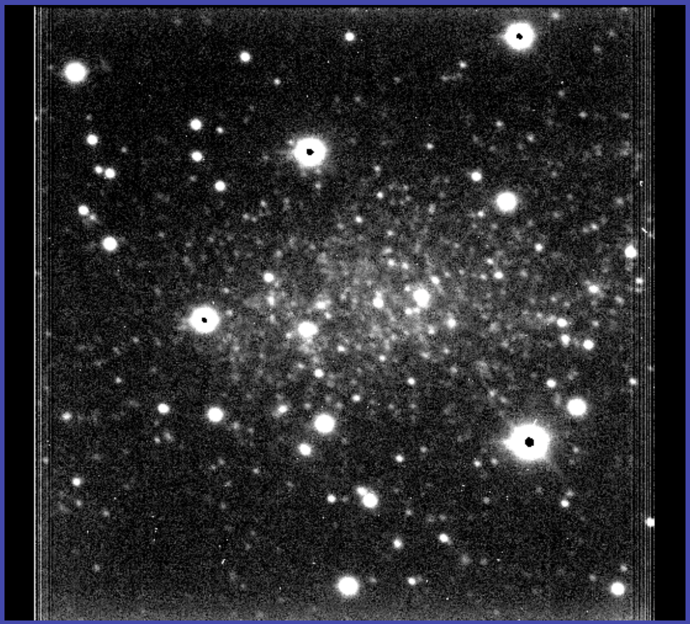


SMC: 60 pc

Dwarf Ellipticals

Most common type of galaxy in the local Universe

low mass, low surface brightness



A. Oksanen, 2.6 meter Nordic Optical Telescope

Sgr Dwarf: near plane of Milky Way
About 24 kpc distant
Discovered 1994 (Irbata, Gilmore and Irwin)
Nearest galaxy to the Milky Way

Spirals

Typically 10^{10} to 4×10^{11} M_O

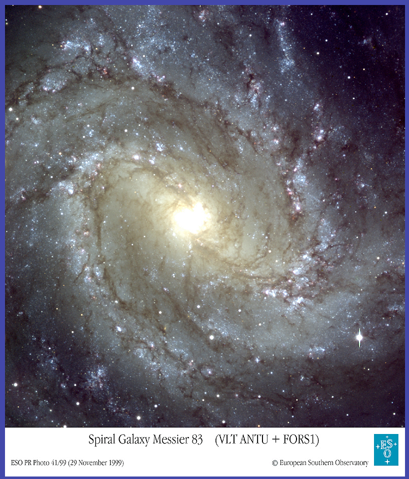
5-50 kpc in diameter

Types: S0,a,b,c

M102: S0

M65: Sa

M100: Sc



M83: SB

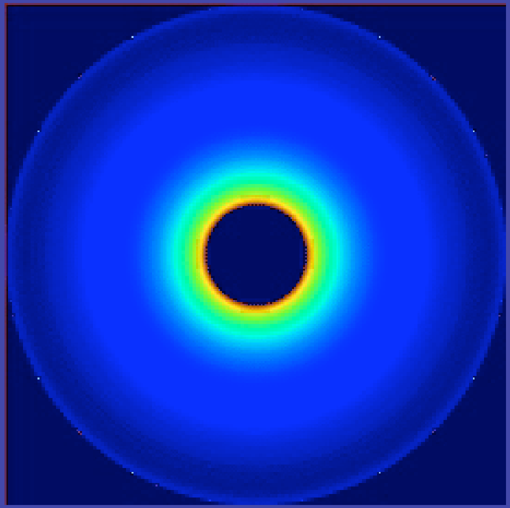
Density Waves

How do spirals get their shape?

Spiral arms produced by density waves – similar to slowdowns on the highway

radially-varying, azimuthally-dependent gravitational perturbation can distort initially smooth, differentially rotation disk into spiral pattern

Compression in the density wave causes star formation



http://www-int.stsci.edu/~godon/self.html

Stellar Nurseries

New stars are formed in spiral galaxies in the galactic disk, where the density of gas is highest.

Generally stars are formed in groups from clouds located in the densest part of the stellar disk, the spiral arms.

Elliptical galaxies are mostly composed of older, Pop II stars. Star formation rate low

Disturbances (galactic collisions for eg.) can greatly increase star formation rate.

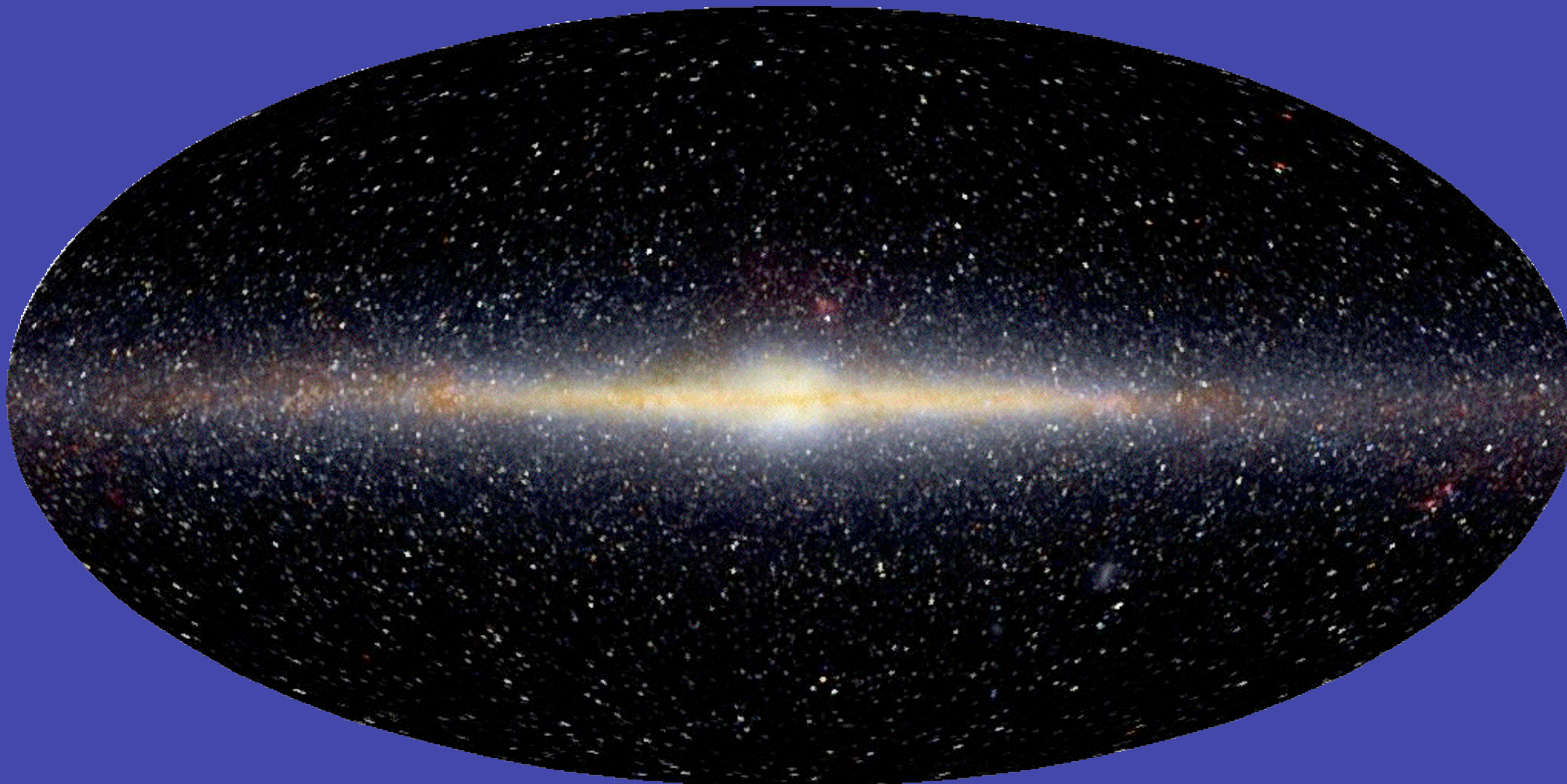
The Milky Way

The Milky Way is the best-studied galaxy; also difficult to study since we're embedded in the thickest part of it

The disk of the Milky Way (visible to the naked eye) has the appear of a glowing band

In the IR it looks different

The IR Milky Way



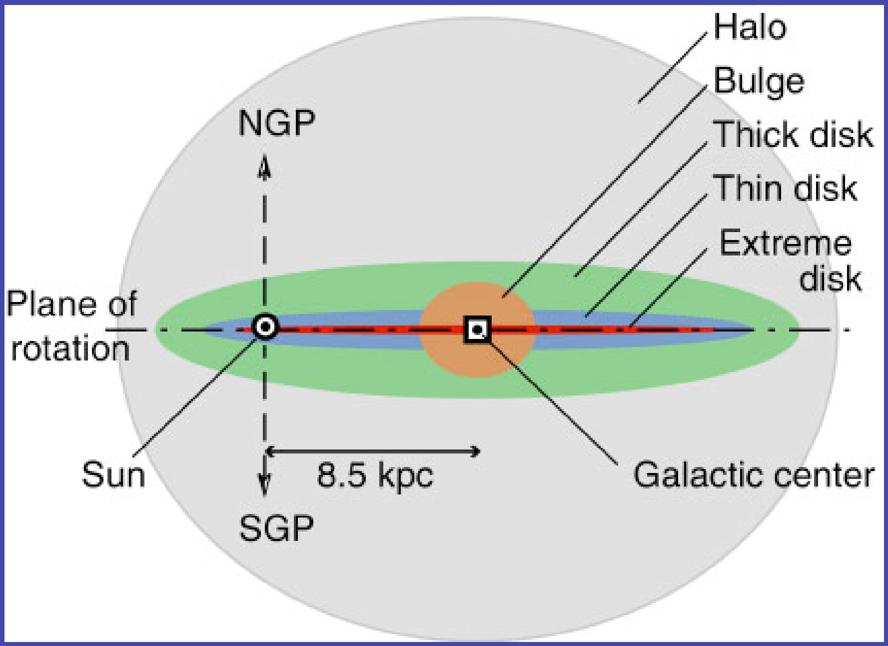
IR view of the Milky Way from the DIRBE experiment on COBE. The Milky Way clearly appears as an edge-on spiral to COBE since the IR can penetrate through the gas and dust and give a good view of the Galactic center and the disk.

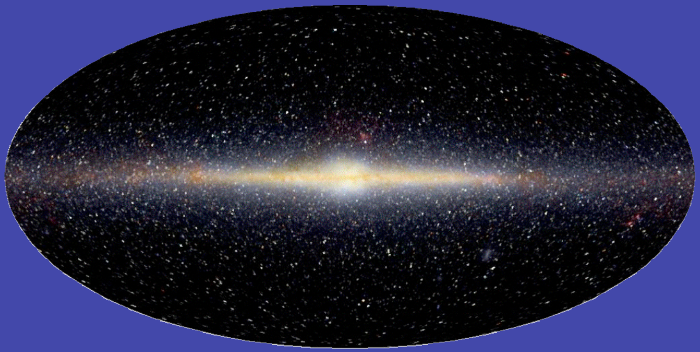
Milky Way: Stats

Diameter	~23 kpc
Period of Rotation	2.5×10^8 years
Total Mass	1.8×10^{11} $M_\odot$
Gas Mass	8×10^9 $M_\odot$
Age	1.2×10^{10} years
Number of Rotations	48
M/L	10

Component	Energy Density (10^{-12} ergs cm^{-3})
Starlight	0.7
Turbulent Gas	0.5
Cosmic Rays	2
Magnetic Field	2
BB radiation	0.4

Components

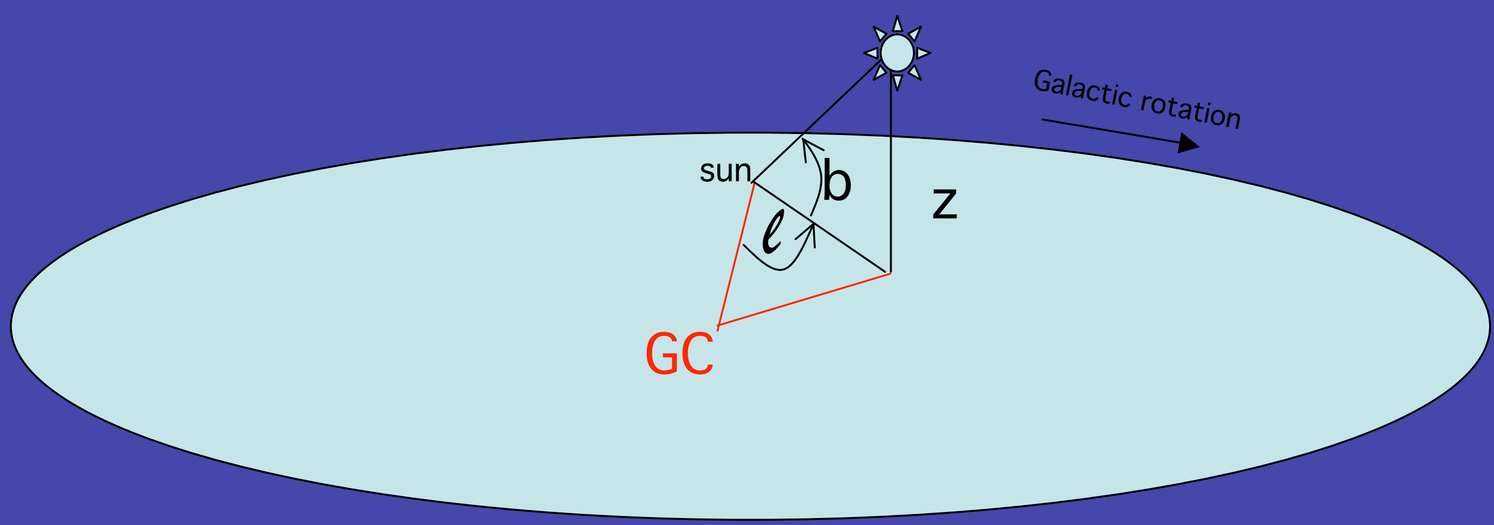




Component	R (kpc)	h (kpc)	Characteristic
extreme disk	25	0.1	dense gas & dust clouds, large Vrot, low Vz
thin disk	25	0.3	stars with high Vrot, low Vz
Thick disk	25	1.0	stars with relatively high Vrot and Vz
Bulge	5	5	metal rich globulars
Halo	100	100	Stars and 170 globulars; low Vrot, high Vz, high eccentricity

Galactic Coordinate System

Galactic coordinates given in longitude, latitude (ℓ, b) defined as



Stellar Populations

Walter Baade divided stars in Andromeda galaxy into 2 distinct populations based on kinematics and location:

Population I: in Galactic disk; open clusters

Population II: in bulge and halo; globular clusters

Pop I stars are young, metal rich stars; Pop II stars are older, lower luminosity, and low metal content.

Population III stars: no metals at all. (none known)

Metallicity serves as a tracer of age

Open vs Globular Clusters

Open Clusters are irregular, gravitationally bound groups of Population I stars.

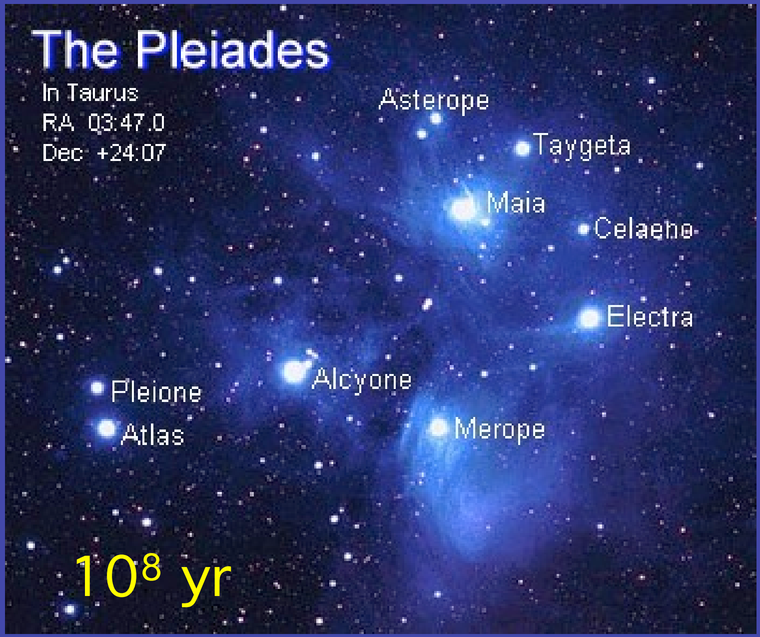
- located in disk of spiral galaxies
- contain OB stars

Globular Clusters are spheroidal groups of older, low mass, Population II stars

- Distributed around galactic center
- no OB stars

Assume: Stars in clusters are co-eval

Examples



Pleiades: Open Cluster
irregular shape
gas & dust
100-1000 stars

M13: Globular Cluster
spheroidal shape
no gas or dust
10^5 stars

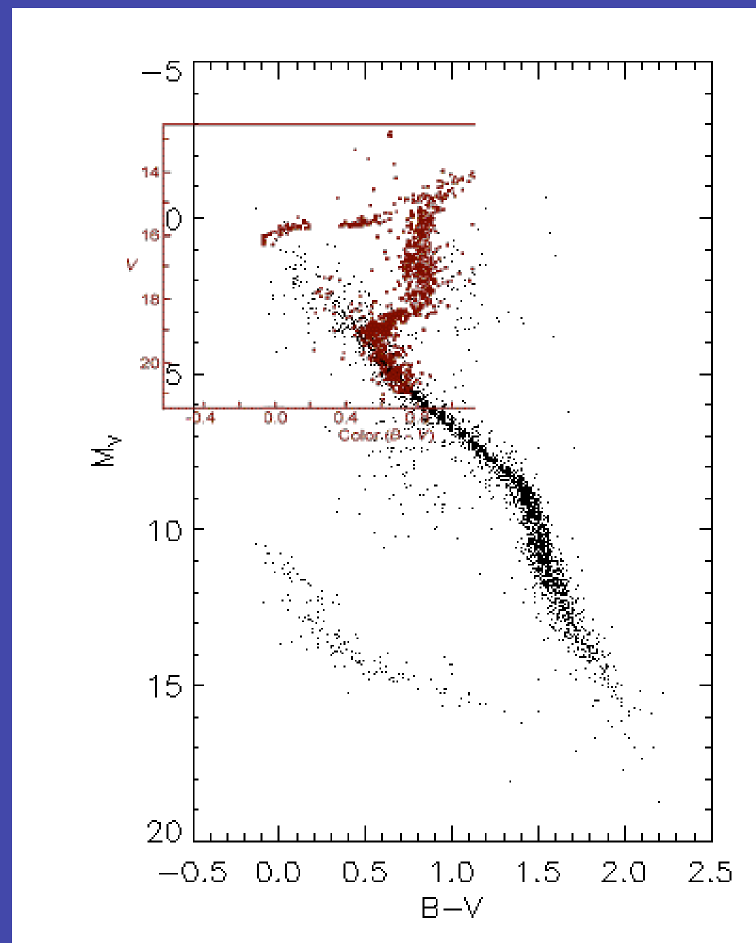
IntraGalactic Distances

Distance measurements within the Milky Way can be done via various means:

Method	How it works	Accuracy	Comments
trigonometric parallax	Measure annual parallax of nearby stars against distant stars	very high	only closest objects (D<1kpc for Hipparcos)
Main Sequence Fitting	Construct HR diagram for stellar group, compare with theoretical MS	Good	contamination by non-cluster stars
Stellar Spectral fitting	Observe spectrum of star, compare to computed spectrum to determine luminosity of star and hence distance	moderate	distant objects if bright enough, but uncertain corrections for extinction and uncertainties in spectral types
Cepheids	variable stars whose periods are proportional to their luminosities	Good	

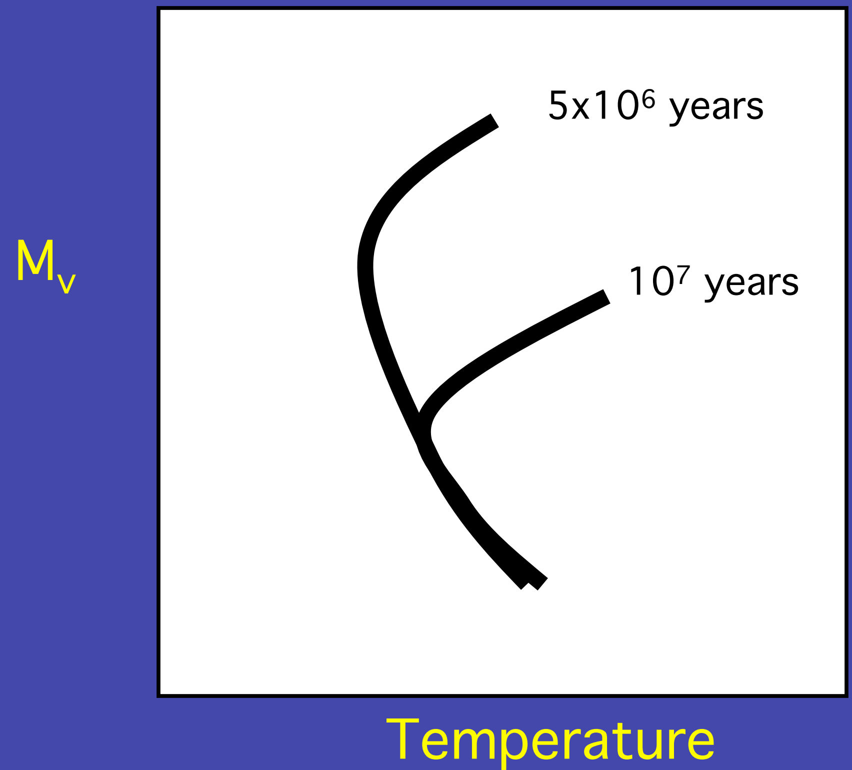
Main Sequence Fitting

Compare observed cluster HRD with calibrated cluster HRD, match stars with same colors and determine distance modulus (m-M)

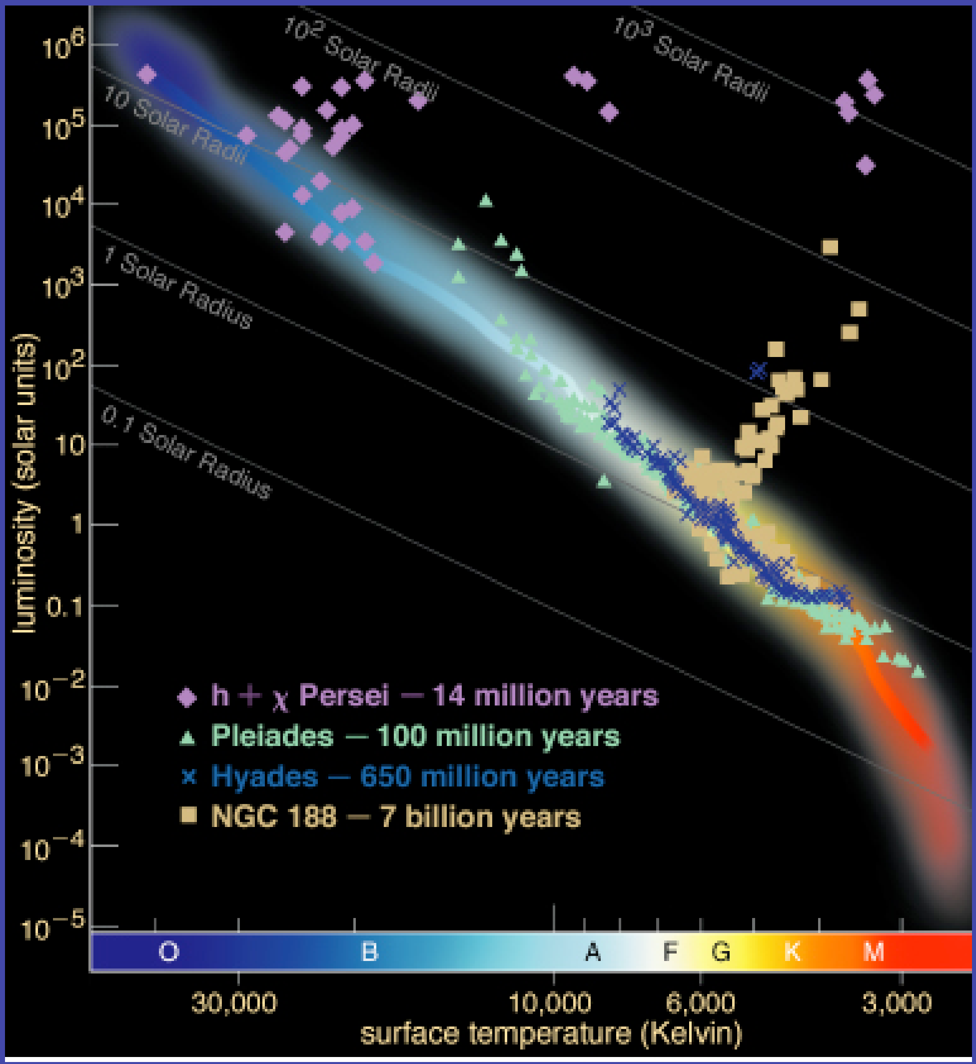


Dating Stars

Ages of stars in clusters can be determined by measuring the main sequence turnoff in the cluster HR diagram.



Age Comparisons



Agesof stars best measured for cluster members.

Determined by position of main sequence turnoff plus stellar evolution models

Assumes all stars coeval (at least for most massive stars)

The Interstellar Medium

ISM: Material between stars

- 99% gas (mostly H and He), 1% dust by mass
- comprises about 15% of the visible mass of the Milky Way
- Mostly confined to thin disk (~250 pc in thickness)

Region	Particle Density (cm^{-3})	Temperature (K)	Filling Factor
diffuse clouds	20	100	5%
intercloud medium	0.1	8000	25%
Shocked gas	10^{-4}	10^{6}	70%
molecular clouds	10^{3}-10^{6}	10-10000	<1%
Earth's atmosphere, sea level	4×10^{19}	290	

The Hot ISM

ISM heated by

- explosions (SNe)
- kinetic shocks (winds, stellar motions, cloud motions)
- ionization (HII regions)

Thermal X-ray maps provide a good tracer of the history of these processes

X-ray All Sky Surveys

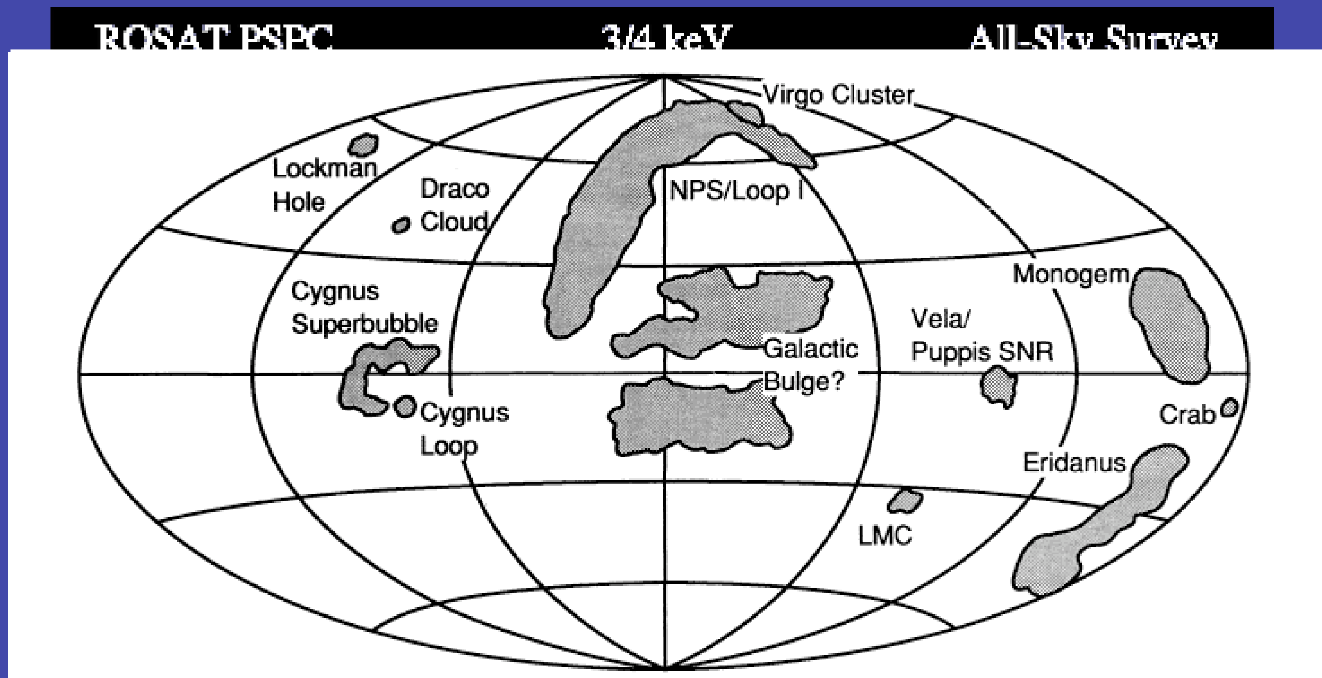


FIG. 6.—Sketch identifying the main features seen in Fig. 5, in the same projection

ROSAT made the 1st all sky imaging survey of soft X-ray background (0.2-2.4 keV)

Components of the Soft XRB

The Soft X-ray Background (SXRB) is composed of:

•0.1 <E< 0.3 keV: thermal emission from hot (~106 K) plasma.

✓ hot bubble in the disk of the Galaxy which *surrounds* the Sun (but was not created by the Sun) and extends from ~50 pc to ~200 pc in different directions.

✓ an extensive distribution of this plasma in the *halo* of our Galaxy.

•E>1 keV: SXRB a superposition of many unresolved discrete extragalactic sources

•0.5<E<1 keV: extragalactic discrete sources and Galactic emission from hot plasma contribute to the observed flux.

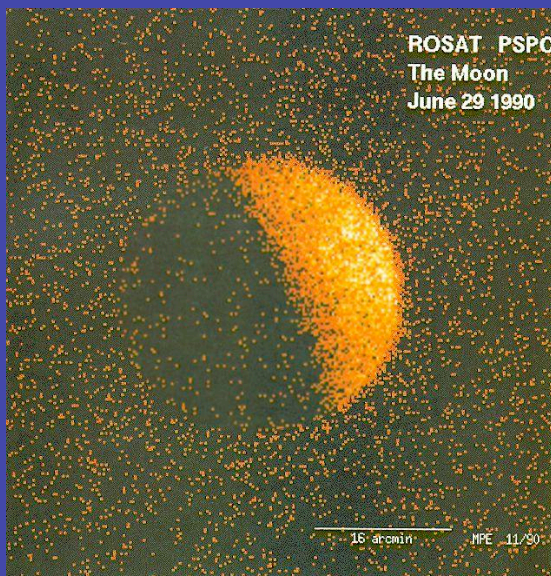
http://imagine.gsfc.nasa.gov/docs/science/know_l2/diffuse_background.html

Distances to the SXRB

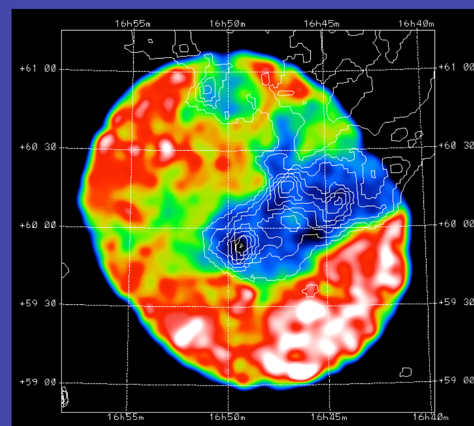
Generally difficult to determine distances to diffuse emission.

One way to constrain distance to the SXRB: see if the emission is shadowed

ROSAT image of the moon showed some of the SXRB is outside the solar system



Schmitt et al.1991



Burrows & Mendenhall 1991

ROSAT image of the Draco cloud clearly shows shadow in the SXRB produced by the cloud.
Cloud is about 900 ly from the sun and about 600 ly from the Galactic disk.
1st determination of hot Galactic halo component

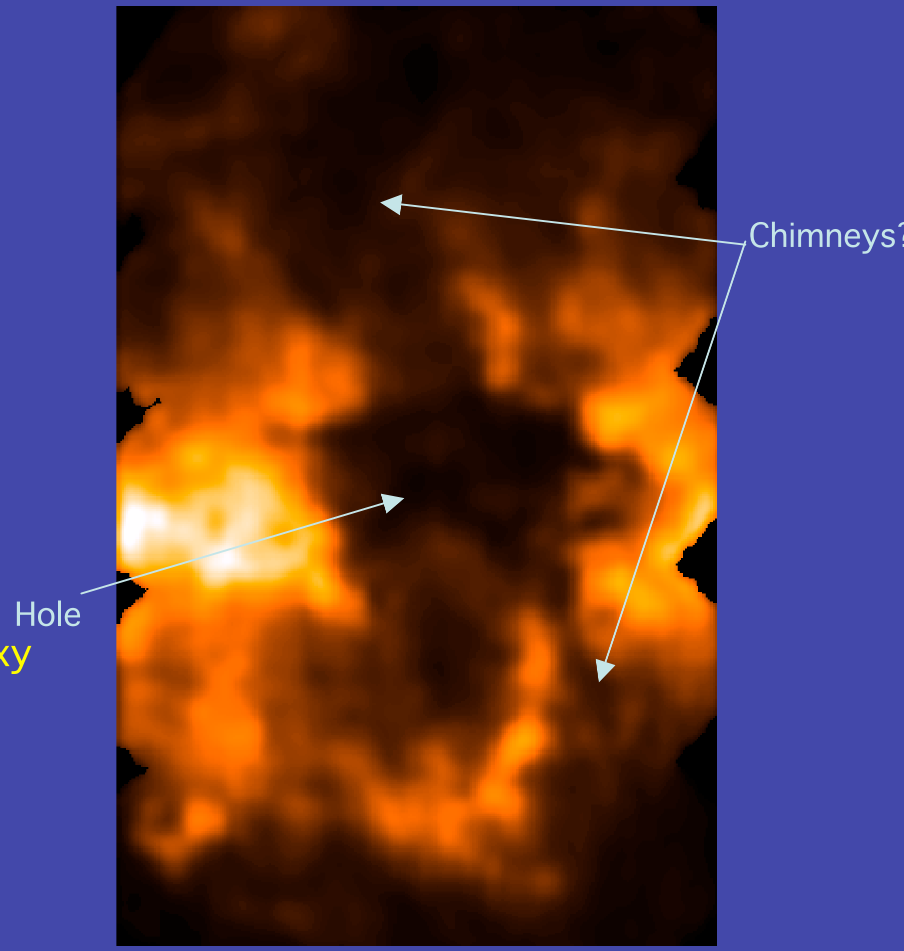
A Hole in the Galaxy

Radio observations of H 21-cm emission (electronic spin-flip transition) shows a hole of very low H density in the Milky Way lying 7 kpc from the Sun and 10 kpc from the Galactic Centre, with a diameter ~700pc - through the disk of the Galaxy.

Possible Causes:

- collision with a cloud or small galaxy?
- GRB?

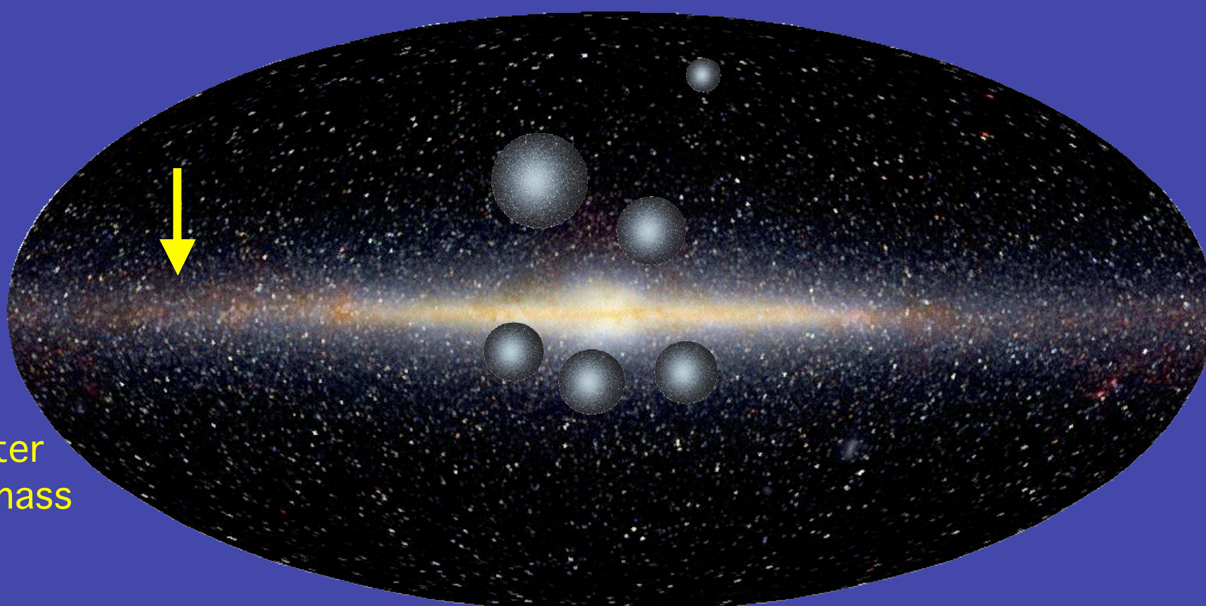
Possibly feeds hot gas from the disk of the Galaxy to the halo...



Finding the Center

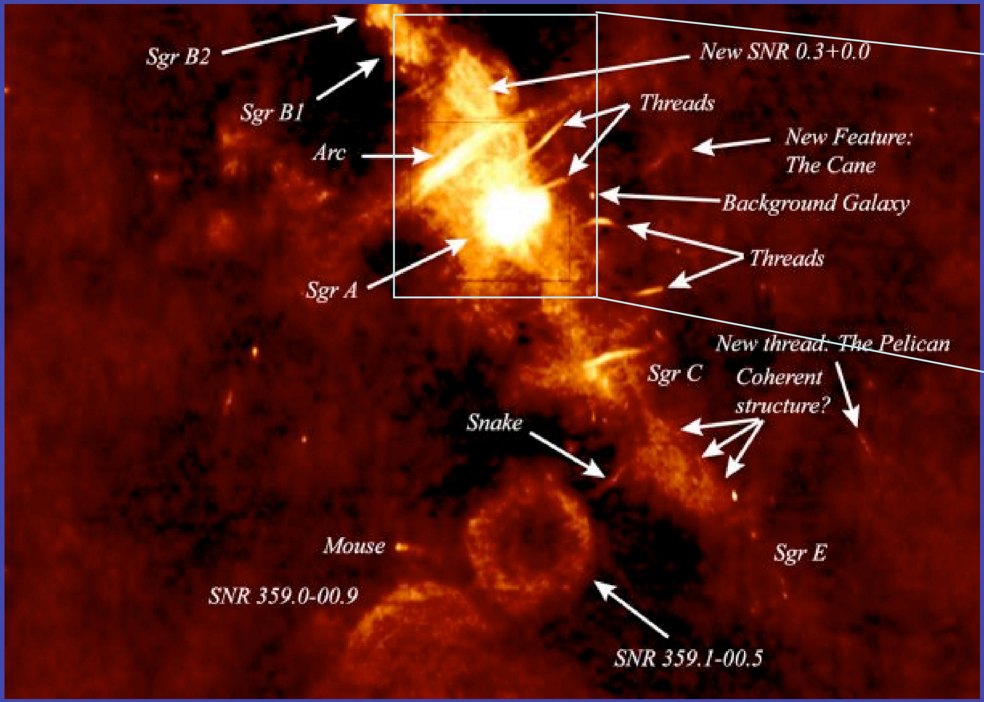
The center of the Milky Way is difficult to determine since we are inside it.

Our location relative to the center of the Galaxy was determined by mapping out globular clusters, which are seen to cluster around a point in the sky about 8 kpc distant from us.



The Galactic Center is the center of mass of the system of globulars

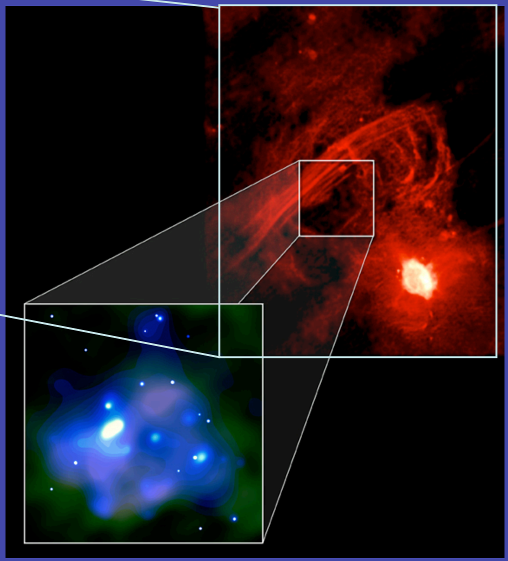
Radio view of the Galactic Center



N. E. Kassim, D. S. Briggs, T. J. W. Lazio, T. N. LaRosa, J. Imamura (NRL/RSD)

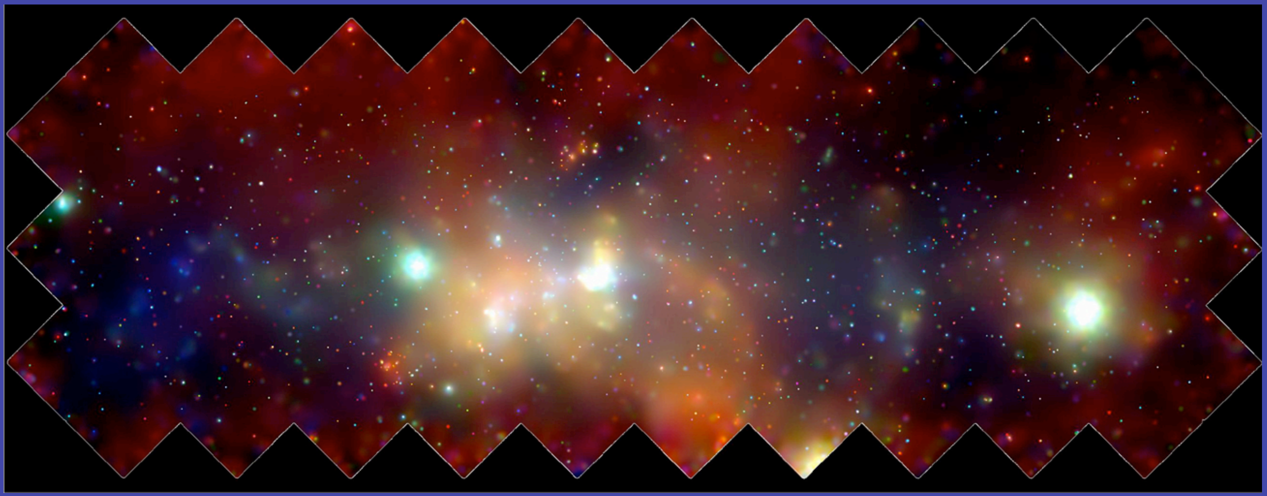
4x4 degree region around the GC. The Galactic disk runs diagonally from upper left to lower right

X-ray (blue): NASA/CXC/Northwestern /F.Zadeh et al.; Millimeter Wavelength (green): Nobeyama/M.Tsuboi; Radio (red): NRAO/VLA F.Zadeh et al.



Galactic Center Radio Arc and the "Arches".
Bright because of ionized plasma constrained to flow along magnetic field lines?
Chandra shows apparent confinement of hot plasma

X-ray View of the Galactic Center



Chandra X-ray color map of 2x0.8 degrees around the Galactic Center

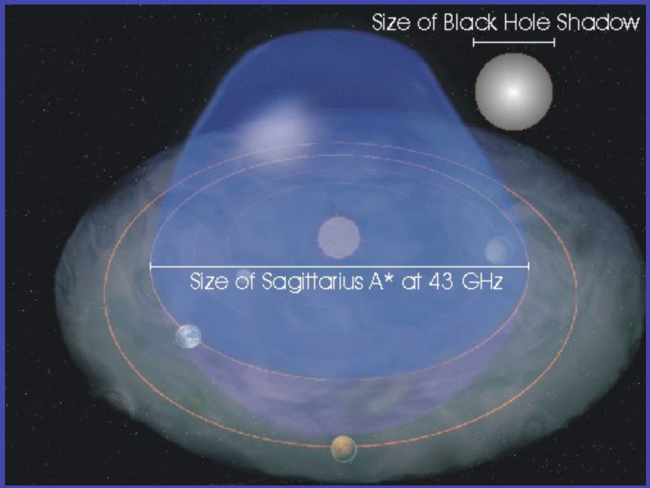
- hot diffuse gas enriched with metals flows to rest of Galaxy?

The Galactic Center and Sgr A*

Near the identified center of the Galaxy a compact non-thermal radio source was identified: Sgr A*

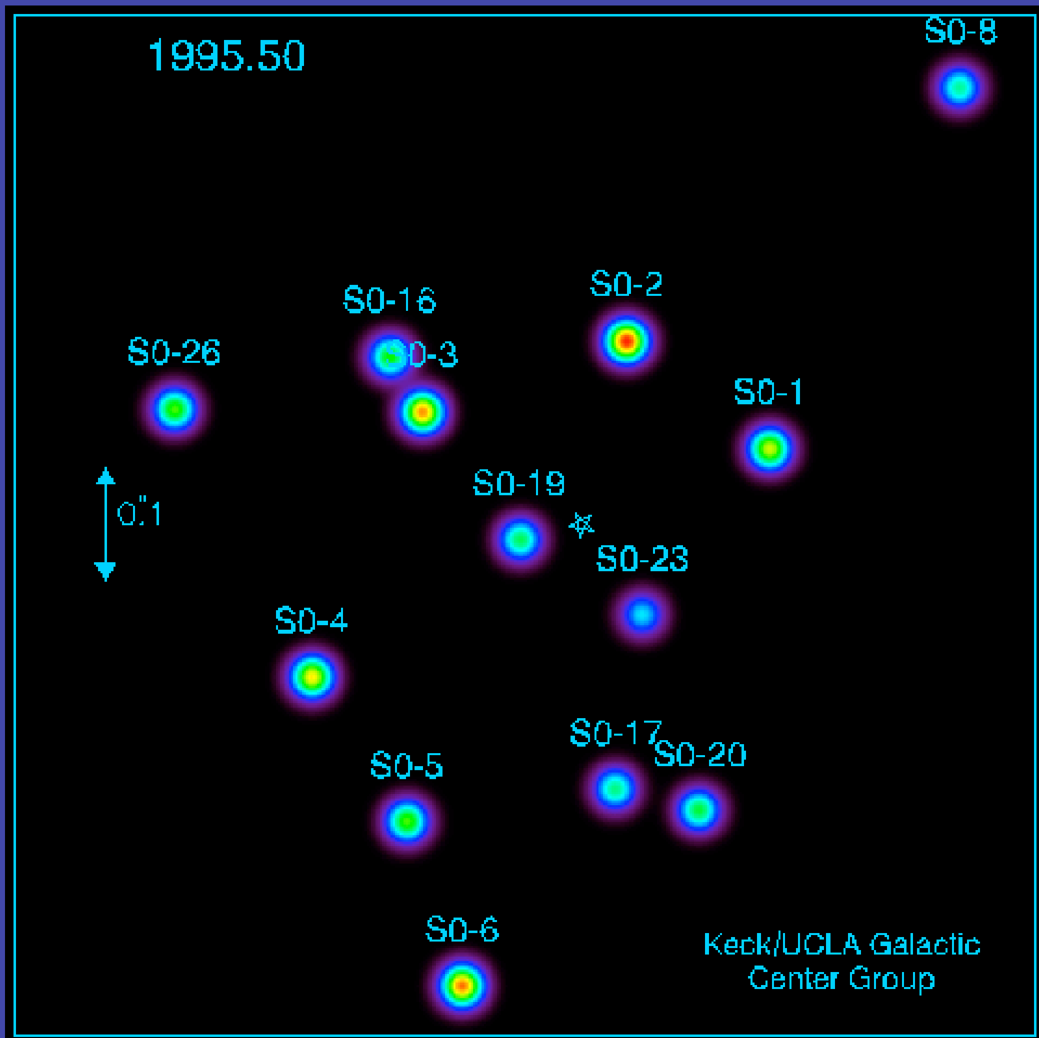
It's believed to be associated with a 1-4 x 10^6 M_O black hole

Strangely underluminous: $L/L_{eddington} \sim 10^{-10}$



Sgr A* recently resolved by the VLA
Diameter of about 2AU
(~24 R_s)
(Bower et al., 2004, Science 304, 704)

Orbiting Sgr A*



from http://www.astro.ucla.edu/~jlu/gc/pictures/orbitsMovie.shtml

A 2.2 micron animation of the stellar orbits in the central parsec. Images taken from the years 1995 through 2004 are used to track specific stars orbiting the proposed black hole at the center of the Galaxy.

These orbits measure the mass of the black hole as 4 million $M_{\odot}$.

Especially important are

- S0-2, which has an orbital period of only 15.02 years, and

- S0-16, which comes a mere 90 astronomical units (about 237 R_s) from the black hole.

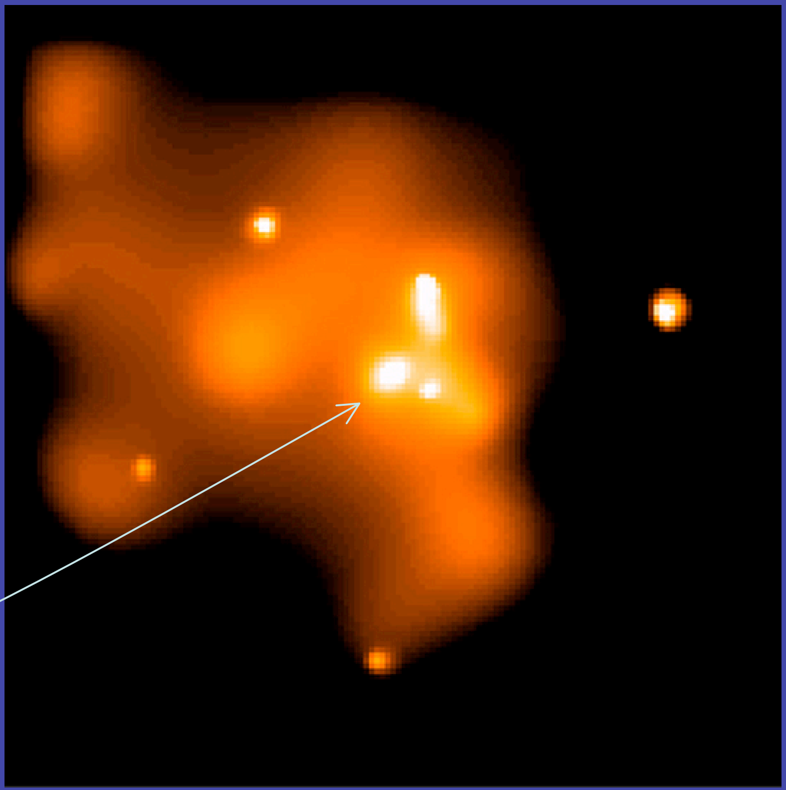
Ghez, A. M., Klein, B. L., Morris, M., & Becklin, E. E. 1998, ApJ, 509, 678

X-rays from Sgr A*

Chandra detects X-ray emisson from Sgr A*.

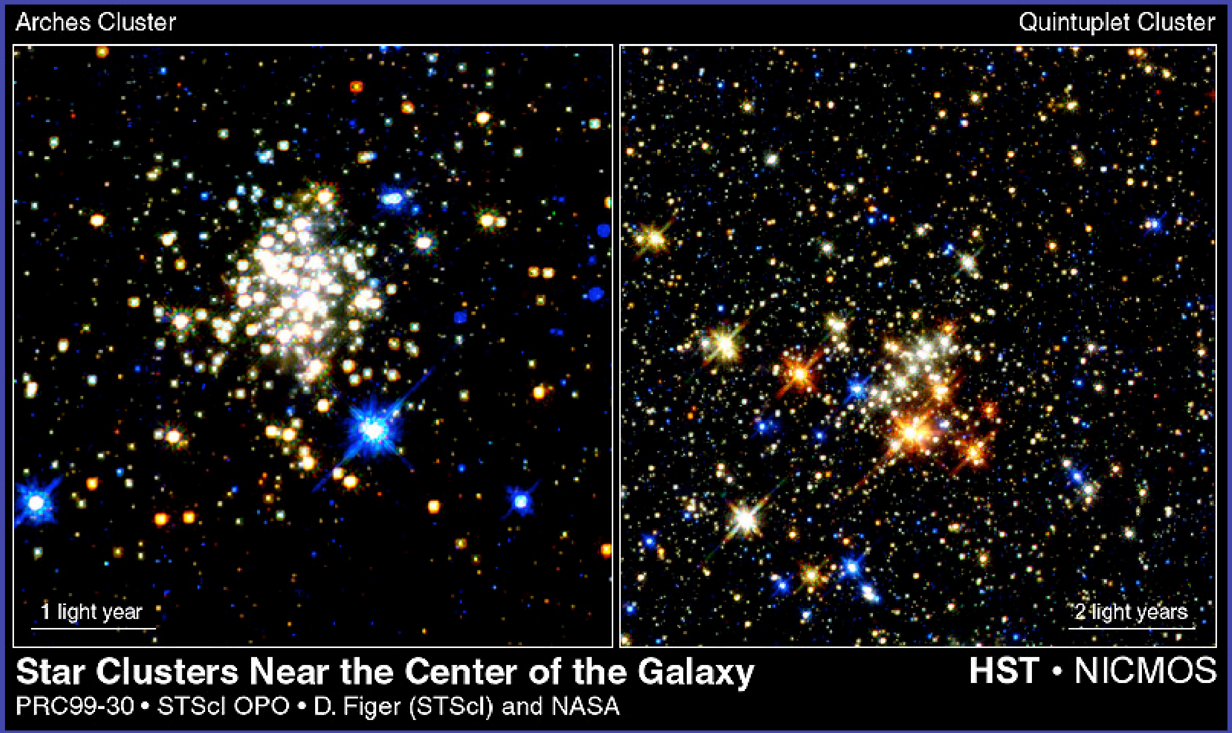
- Black hole not completely quiet?
- What's it eating?

Sgr A*

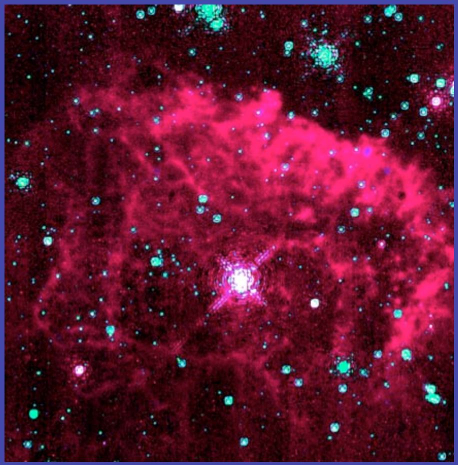


Baganoff et al. 2000

Galactic Center Clusters



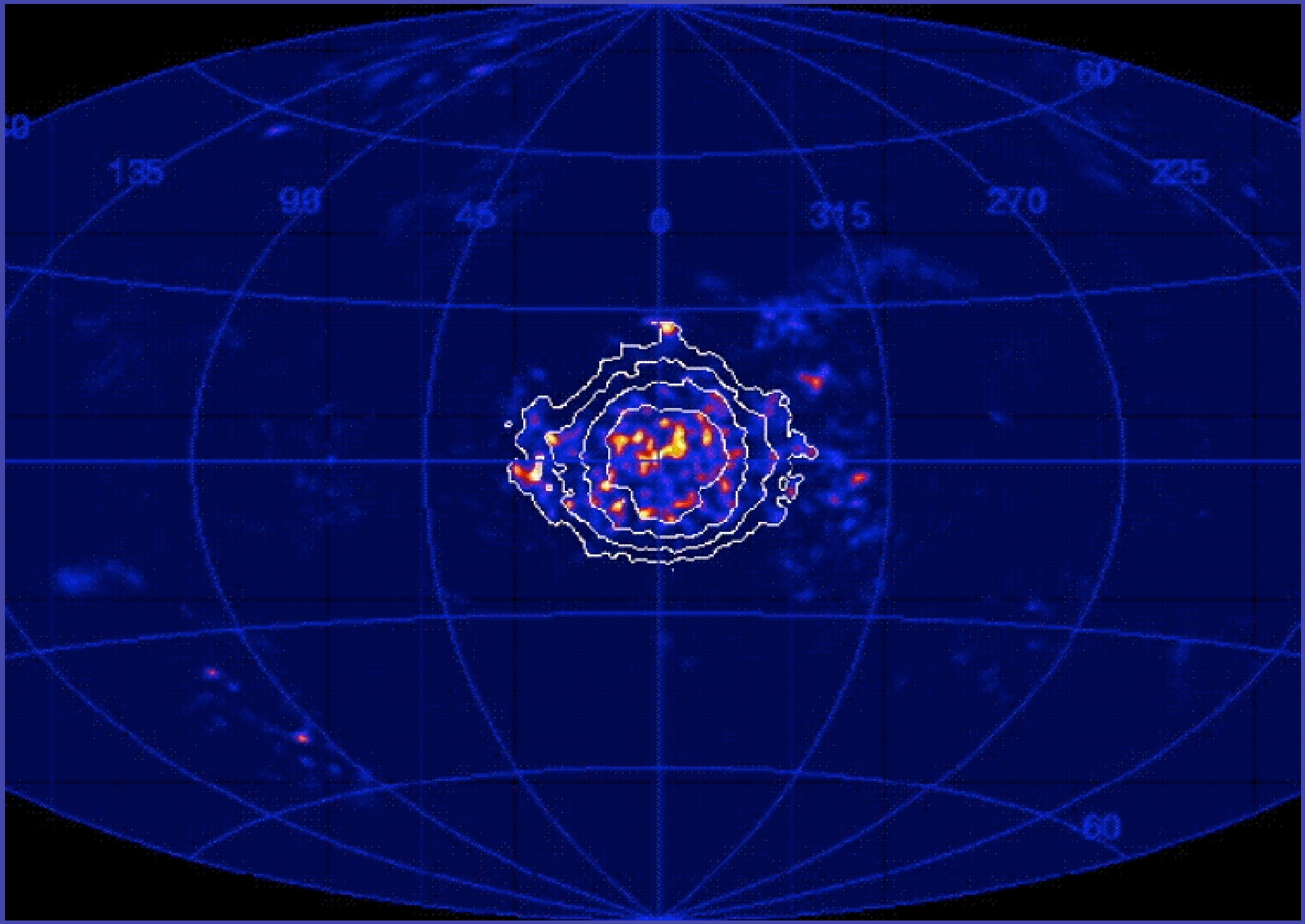
The Galactic Center is an active region of star formation, and contains some of the most massive known star clusters: the Arches cluster, and the Quintuplet cluster



One member of the Quintuplet, called the Pistol Star is one of the most massive & luminous stars known.

Figer et al.

Annihilation



J. Knödlseder (CESR) and SPI team; INTEGRAL

A map of the Galaxy in the 511 keV line produced by electron-positron annihilation. Anti-matter confined to a relatively small location near the Galactic Center

Galactic Dynamics

The Sun revolves once per 2.5×10^8 yr around the GC

Since the formation of the solar system sun has made about 20 Galactic rotations

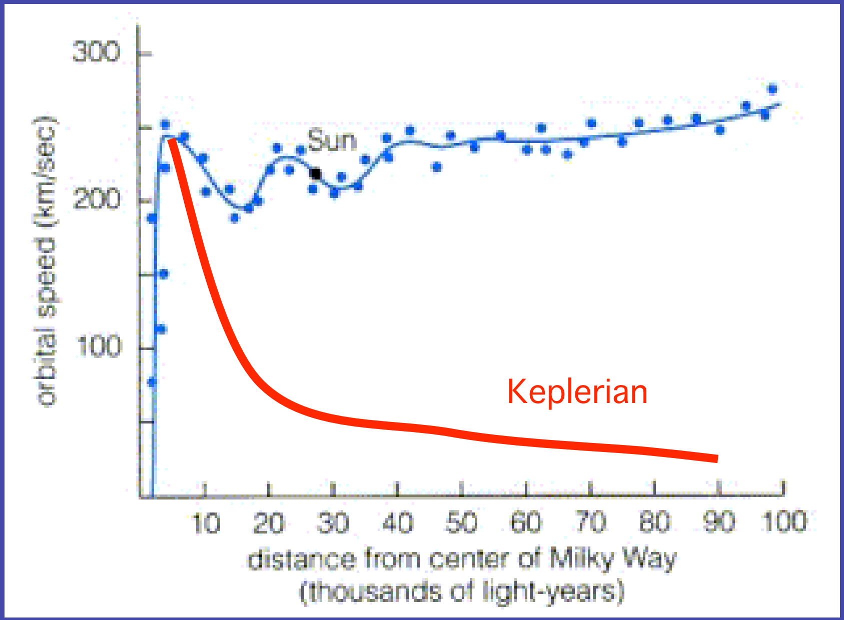
beyond about 8kpc from the GC, disk of Galaxy undergoes differential rotation where the period varies with increasing distance from the GC

In the halo objects orbit the galactic center: “swarm of bees”

Rotation Curves

Solid Body rotation: $V \propto r$

Keplerian rotation: $V \propto \frac{\sqrt{M}}{\sqrt{r}}$



Flat rotation curve implies that M increases as r

Missing Mass/Dark Matter

- Mass in visible stars much less than the mass implied by the flat rotation curve
- Astronomer Jan Oort (1932) found the total mass density near the sun of 0.092 M_O/pc^3 from studies of the motions of K giants, compared to 0.038 M_O/pc^3 estimated from the visible stars: Missing Mass
- Estimates of the mean surface mass density (from star counts) to the mean surface brightness near the sun yields a mass-to-light ratio = 5 $M_O/L_O \Rightarrow$ most of mass in solar neighborhood from lots of low mass stars
- Perhaps missing mass composed of dark stars, planets, etc? Where is it located?
- Perhaps non-Newtonian gravity?

Dark Matter in the Milky Way

- Total mass of luminous matter in the Milky Way: ~200 billion $M_{\odot}$.
- Total mass of Milky Way: ~600 billion $M_{\odot}$.
- Most of Milky Way non-luminous

Collisions and Interactions

Stars within galaxies are isolated ($\alpha = R_{interstellar}/R_* >>> 1$):

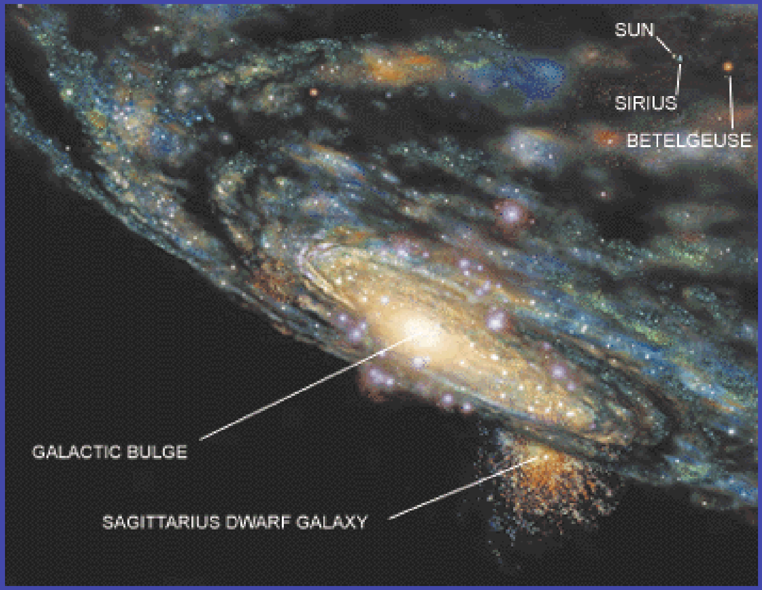
eg Sun/Proxima Centauri have $\alpha \sim 6 \times 10^7$

Galaxies are not isolated ($\alpha > 1$):

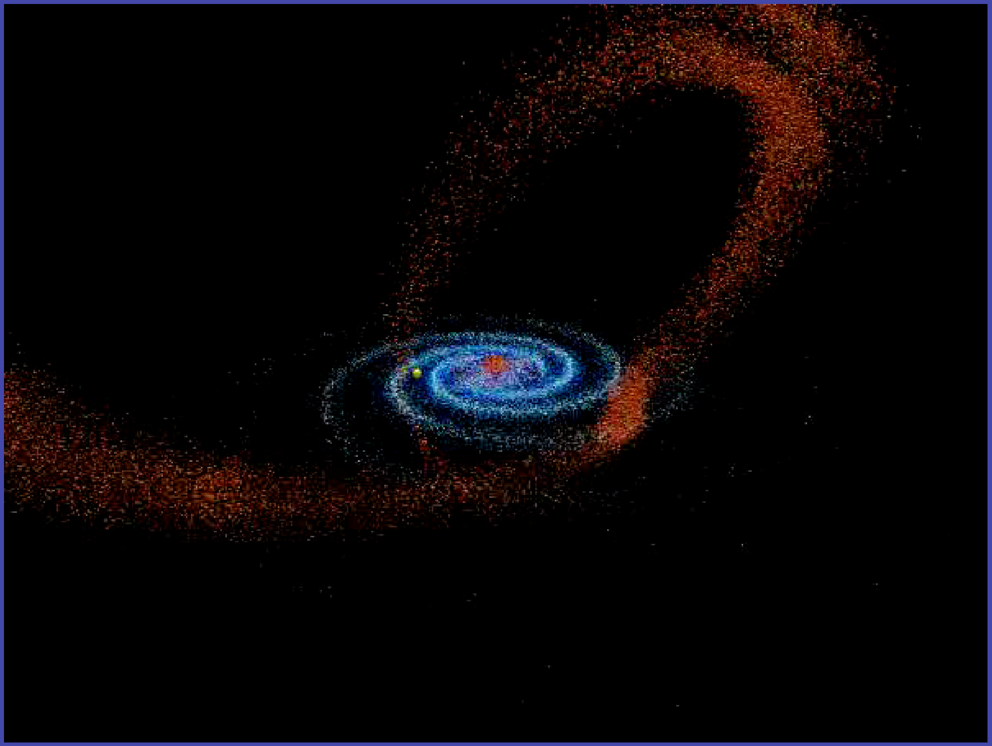
eg Milky Way/Andromeda have $\alpha \sim 13$

Galaxies can interact and collide

Milky Way/Sgr Dwarf



Artist's conception of the Sgr Dwarf/Milky Way merger



Simulation of tidal streams associated with Sgr Dwarf (David Law)

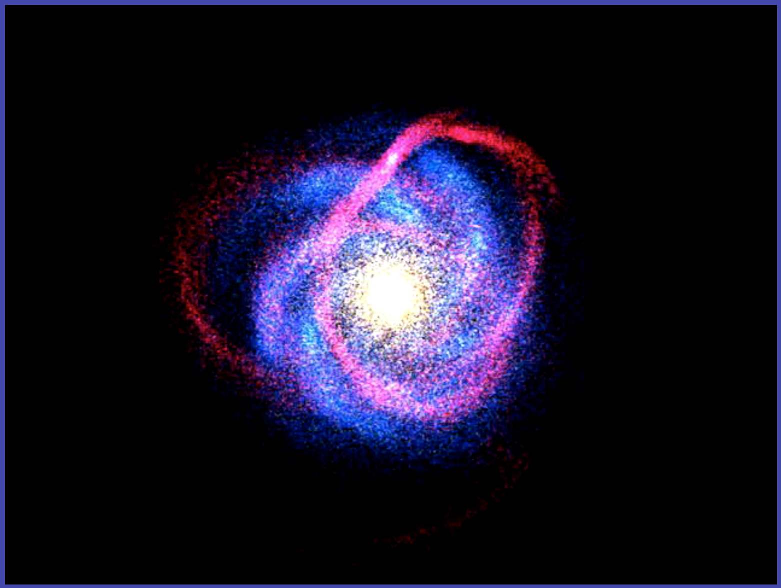
Milky Way/Canis Major Dwarf Merger

N. F. Martin et al. (2004, MNRAS 348 Issue 1 Page 12) found a spiral shaped overdensity of M giants close to the Galactic plane from a 2 micron survey (2MASS) in the constellation Canis Major, along with streams of M giants apparently connected with the overdensity.

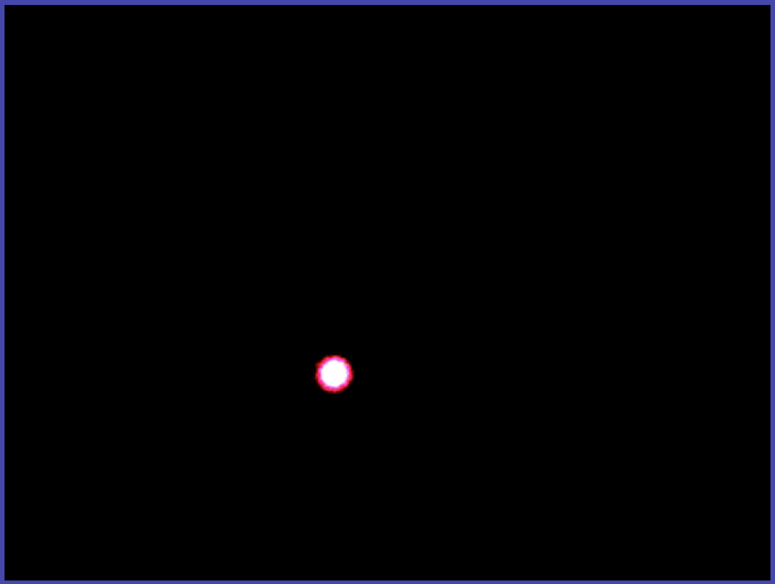
Remnants of a small galaxy (10^9 M_O) that got swallowed & tidally disrupted by the Milky Way?

Or perhaps illusion created by the warp of the disk of the Milky Way?

Simulation of the CMa overdensity



Simulated view of the tidally disrupted CMa galaxy



Simulation of the disruption of the dwarf galaxy

If real, suggests that the disk of the Milky Way might be built up by swallowing smaller galaxies

Milky Way/M31 Merger

The Milky Way and M31 should merge in about 3 billion years

M31 moving towards the Milky Way at 500,000 km/hr

http://www.cita.utoronto.ca/~dubinski/Gravitas/spiralmetamorphosis.html

1 billion years after merger, remnant is an elliptical galaxy

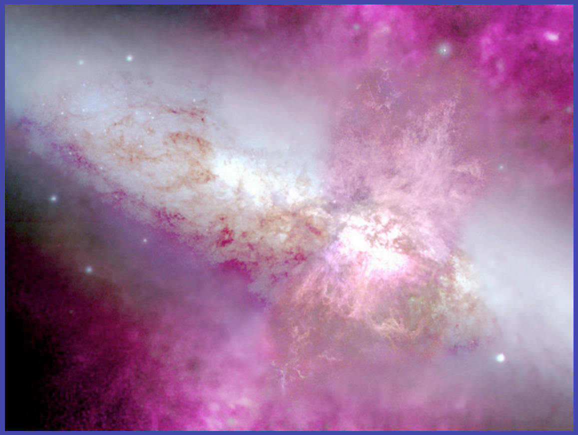
Starburst Galaxies

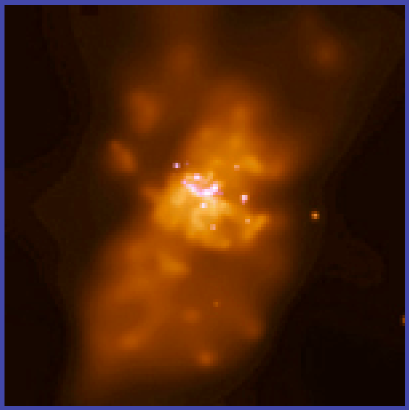
SBG: Galaxy experiencing intense, short lived period of star formation

SFR 10-100x greater than normal

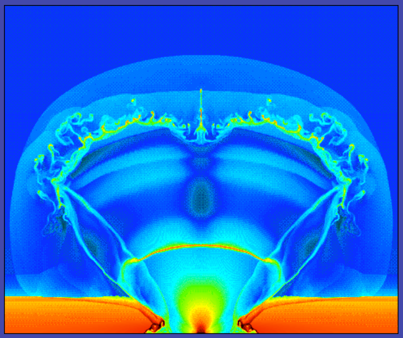
Example: M82

M82 is an irregular galaxy (a "disk" irregular) which has SFR~10 SFR_{MW}.





Rapid SF produces lots of SNe which can blow a hole through the galaxy, and feed the IGM.



Formation of Galaxies

How do Galaxies form? Stellar abundances & distributions allow "Galactic archeology"

- Eggen, Lynden-Bell & Sandage (1962): studied dynamics and abundances of high-velocity stars; as Z decreases, eccentricities and kinetic energies increased while angular momenta decreased

- metal poor stars reside in a halo which formed as the proto-galactic gas cloud started to collapse

Challenge to the Standard Picture

Searle 1977: Globular clusters have a wide range of metallicities, independent of radius from the Galactic center.

- halo built up over extended period from protoclusters of 10^8 M_O?
- Can fossil remnants from this build-up be identified and studied?

Overview of Milky Way Evolution

Dark-matter halo forms first

Stellar bulge & central black hole form

Disk form; star formation peaks (probably $z>1$); strong metal gradient

Halo stars form (very low metallicity)

Globulars form (some produced by collisions with satellite galaxies which had their own metallicity evolution)

key discriminant: iron-to-hydrogen [Fe/H] ratio; indicator of rate of SNe, not necessarily age

Summary

Galaxy-Galaxy interactions important

The centers of spiral galaxies are strange places: Black Holes, massive stars, magnetic structures...

Rotation curves of galaxies, other dynamical measures probably indicates presence of non-radiating matter